NAVOCEANO Seahorse AUV Participation in the Giant Shadow Experiment

J. E. Dzielski, M. J. Bregar, D. L. McDowell, R. P. Swanson, Jr.[1], S. Tangirala, C. R. Zentner

Applied Research Laboratory
Penn State University
P. O. Box 30
State College, PA 16804-0030
U. S. A.
Phone: 814-863-4794, e-mail: dzielski@psu.edu

[1]Naval Oceanographic Office
1002 Balch Blvd., Bldg. 9322
Stennis Space Center, MS 39522-5001
U. S. A.
Phone: 228-689-8095, e-mail: swansorr@navo.navy.mil

Abstract-During January of 2003, the first of the Seahorse vehicles was loaded into a missile tube onboard a Trident Submarine and successfully launched. This launch was part of a larger experiment called Giant Shadow, which included a number of U.S. Navy and industry participants. As part of this experiment, the Seahorse conducted two missions. The first mission consisted of two components and was conducted immediately following the launch from the submerged submarine. The first component was a minefield survey. After completing the survey, the AUV surfaced and transmitted data to a support craft via a radio link. The second component of the first mission was a simulated Q-route survey. This survey was conducted in preparation for the second mission that involved the delivery of a set of payloads to a team on-shore and the transfer of a different payload back to a support ship. These missions are described in greater detail in the paper along with some of the testing leading up to the final experiment.

I. NAVOCEANO SEAHORSE AUV

ARL/PSU has been actively involved in the development of underwater vehicles for over 50 years. The laboratory's predecessor, the Harvard Underwater Sound Laboratory, developed arguably the first autonomous underwater vehicle constructed in the United States, the (Mk24/FIDO) in the early 1940s. While predating modern electronics, the vehicle had a basic capability to sense its environment and respond by maneuvering in response to sensor inputs. The laboratory was moved from Harvard to Penn State University in 1945 and continued development of autonomous underwater vehicles under the new name of The Applied Research Laboratory (ARL). During the 1990s, the development of technology for weapon applications was de-emphasized by the Navy and there was a greater interest in vehicles and technology for more general missions. In response to these needs, ARL has developed a number of vehicles during the 1990s ranging in size from 40 lbs to 10,000 lbs. Vehicles are being currently developed that operate over speed ranges covering two orders of magnitude.

After an initial conceptual design phase, in April 1999 ARL began design and construction of an AUV to meet requirements of the Naval Oceanographic Office (NAVOCEANO) of the United States Navy. The mission requirements resulted in a large vehicle 28 feet long and 38 inches in diameter with a range of 500 nmi at 4 knots. The vehicle weighs 10,705 lbs and has a displacement of 10,794 lbs. The design and construction phase of the project lasted 13 months after which a final integration and in-water testing phase began that lasted four months. After that phase, the prototype vehicle was delivered to the U.S. Navy. A second Seahorse vehicle has also been constructed and was delivered in October 2001 and the third is scheduled for sea-trials. The first Seahorse vehicle is shown in Figure 1 prior to shipment for its first in-water tests.

In the following sections, the modifications necessary to allow the Seahorse vehicle to be launched from a vertical tube are described along with the method of launch. Finally, the missions conducted during the Giant Shadow Experiment are described.

Figure 1. The Seahorse AUV constructed for the Naval Oceanographic Office

II. CHANGES TO SEAHORSE VEHICLE TO SUPPORT VERTICAL LAUNCH

A number of modifications were necessary to the baseline Seahorse vehicle to support a submarine launch. Mechanical modifications included the design of a support structure to hold the Seahorse vehicle in a Trident missile tube, modifications to the vehicle to adapt it to the support structure and launch and ejection system, and changes to the Seahorse umbilical. Software changes included modifications to allow operations in a vertical orientation and an entirely new launch sequence to accommodate ejection from the tube and a platform clearance maneuver.

The structural support for the Seahorse in the launch tube consisted of an insert that was mechanically compatible with the Trident submarine missile tube and a set of guides inside the insert to support the Seahorse. The Seahorse support and guides are shown graphically in Figure 2 without the insert for the launch tube. The guides consisted of 4 Delrin-lined steel I-beams arranged in pairs on the top and bottom of the vehicle. The guides on the bottom of the vehicle are separated by a 90-degree interior angle. The guides on the top of the vehicle are separated by an interior angle of 60 degrees. This is to

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accommodate guide shoes that are bolted to structural stiffeners on the vehicle that are spaced at 30-degree increments (due to the 6 payload bays per section). The guide shoes were added to the vehicle to insure proper registration with the tube and to prevent rotation of the Seahorse as it exited the launch tube. The weight of the Seahorse was carried on a collar attached to the Seahorse structure between the first and second payload sections. The collar can be seen attached to the lifting straps in Figure 3. Shown in Figure 4 is a drawing of the float that was designed to insure that the Seahorse would have adequate velocity for control upon exiting the tube and to insure that the vehicle could be ejected from the tube if necessary. The float consisted of an aluminum base with pairs of "whiskers" centered on each of the guide rails and sections of syntactic foam that could be added or removed to change the buoyancy of the float in increments of 50 pounds. The maximum buoyancy of the float was 450 pounds. The float was designed with a hub-and-spoke opening so that the flow from the propulsor was not significantly deflected laterally but allowed to pass through the float.

One of the major differences between the way that the Seahorse is normally operated and how it was operated during the submarine launch has to do with the initialization of the Kearfott SEANAV inertial navigation system (INS). Normally, the integrated GPS is used to establish the initial vehicle location and orientation. When submerged, this data is obviously not available and program cost and timeline constraints prevented integration with submarine systems. A more serious problem with initializing the INS related to the fact that only Euler angles can be provided through the operating interface of the INS. These angles are not defined in the vertical orientation and the possibility existed for significant initialization errors if an initial attitude command was issued. In the off-hull tests described later in the paper, the capability of the INS to do a stationary alignment was used. In the subsequent tests, upgraded INS software and modifications to the vehicle software allowed the inertial system to be aligned while moving.

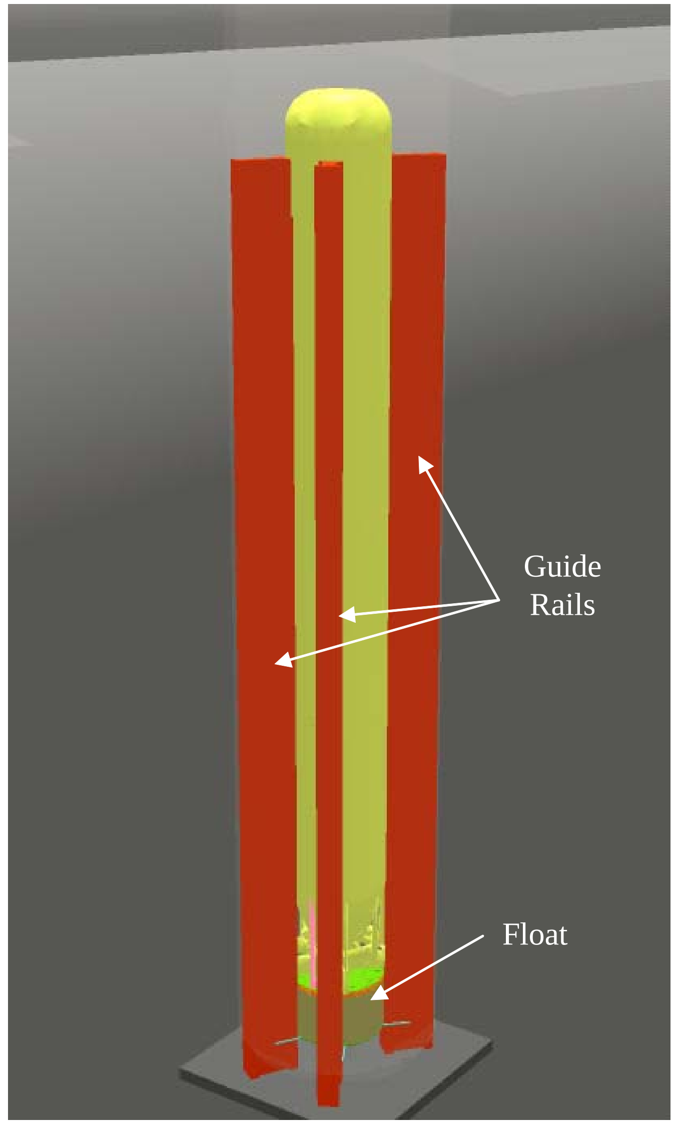

Figure 2. Seahorse support and guides

Figure 3. Seahorse being lifted for insertion into launch apparatus

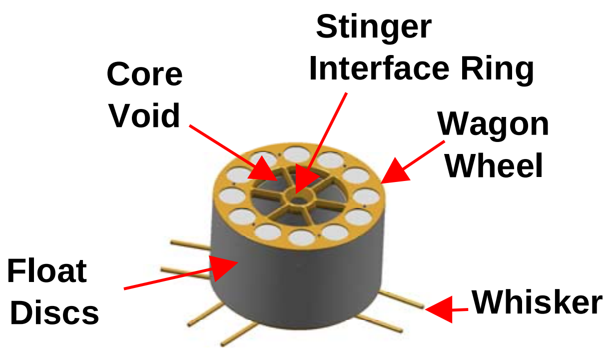

Figure 4. Launch float used to push Seahorse

Another major change that had to be made to support the vertical launch was the implementation of control logic and safety checks appropriate for the tube launch. Normally, the Seahorse begins a mission floating horizontally on the surface. The variable ballast system ingests water until the vehicle sinks to a preset depth where the propulsion motor is started. The launch sequence for the submarine had a number of states. When the test director gave permission, the Seahorse mission software was started and the vehicle controller was commanded to start the propulsion motor. The propulsion motor would run at full speed (about 200 lbs thrust) for three minutes or until released by the restraining mechanism. If the three-minute time expired, it was assumed that the launch had been aborted and the vehicle software returned to a state where the launch sequence could be re-initiated. If the Seahorse was released, the vehicle would monitor progress until it had translated 15 feet as indicated by the depth sensor. At this point the fins were commanded to a maximum dive configuration and the propulsion thrust was reduced to a level consistent with normal operating speed with the collar attached (about 100 lbs thrust). The reason for reducing the thrust was to reduce the speed and hence the vertical distance traveled while the Seahorse was pitching to a horizontal attitude. The full elevator caused the vehicle to pitch in the horizontal plane in such a way that the nose of the body pitched toward the aft of the submarine launch platform. When the Seahorse was within 10 degrees of being horizontal, the normal three-axis control system for the vehicle was enabled. Ten seconds was allowed for the autopilot to stabilize the flight of the vehicle. After this time had expired, a 90-degree starboard turn was initiated. This turn caused the Seahorse to clear the launch platform to the platform's port side. There were a number of safety checks that were conducted during the launch sequence to detect if the vehicle became stuck in the tube and to make sure that the expected sequence of events occurred. In the event of a failure, the Seahorse would have been commanded to remove propulsion power and terminate the mission. If the launch logic detected that the vehicle had cleared the launch tube, the variable ballast system was commanded to pump to the empty state.

One additional feature that was added to the Seahorse vehicle was a set of payload bays that could be opened and closed under the command of the mission software. The original idea was to simulate the launching of a weapon or sensor system from an AUV. The payload mechanism consisted of a cradle that housed a device about three feet long and 12 inches in diameter. The cradle was attached to a lead-screw mechanism that would push the payload clear of the vehicle so that if it was positively buoyant it would float to the surface. The cradle was attached to a standard fiberglass bay cover that opened and closed with the cradle to maintain a streamlined hull. A diver can be seen in Figure 5 handling one of the payload bottles and an open bay can be seen on the submerged vehicle. Originally, the payloads were to be deployed at depth and float to the surface. During the Giant Shadow experiment the Seahorse delivered two payloads to a point off a beach and they were removed by swimmers and replaced with different bottles containing samples to a ship off-shore.

Figure 5. Diver with payload and open bay

III. Preliminary Off-Hull Testing

In order to demonstrate that the Seahorse AUV and the launch system were ready for installation on a submarine, a series of tests were conducted at Bangor, WA, to verify the design and the behavior of the AUV. These tests were conducted during August 2002. The launch assembly that was built to simulate the Trident missile tube is shown being lowered into the water in Figure 6. The Electric Boat Division of the General Dynamics Corporation (GDEB) constructed this assembly along with the launcher installed in the submarine. In order to load the Seahorse into the launcher, a line was attached to a stinger on the AUV's tail, and the positively buoyant vehicle was pulled from the surface and down to the opening on the launcher by a hydraulic winch. Divers aligned the vehicle so that the stinger engaged the float and the vehicle was properly oriented. The haul down mechanism was then used to pull the Seahorse and the float to the bottom of the tube and a pin was engaged with the stinger to hold the float and Seahorse in place. The off-hull testing was planned and coordinated by GDEB.

Figure 6. Test stand being readied for off-hull test series

Six tests were conducted as part of this test series. Two tests were conducted to determine if the Seahorse would leave the launch tube if either the float or the propulsion system failed. Two tests were conducted to determine the contribution made by the float to the exit speed of the vehicle and to select the float buoyancy. Also, two tests were conducted to determine the characteristics of the Seahorse transition to level flight and the platform clearance maneuver. The first three tests were with the full float and the last three were conducted with a float force of 250 pounds.

The current during the tests varied from 0.25 to 0.75 knots perpendicular to the launch exit. The launcher apparatus was oriented so that the direction of local tidal current flowed from the top toward the bottom (perpendicular to the longitudinal axis) of the AUV in the launcher. An exterior skin on the launch stand prevented flow over the vehicle in the vertical tube. Because the vehicle is constrained in the tube, the fins cannot be used to influence the direction in which the vehicle tips over as it leaves the launcher. The direction of the current was selected so that hydrodynamic forces on the vehicle insured that the vehicle pitched in the proper direction as it exited the tube. In addition to verification of the launch system and the vehicle software, the testing gained significant insight into the operation of a vehicle propulsion system in a constrained space and in conjunction with a float that did not fully block propulsion flow.

IV. Readiness Experiment

In December 2002, off Gulfport, MS, a series of readiness tests were conducted prior to shipment of the Seahorse AUV for loading onto the submarine. During planning of the Giant Shadow exercise, it was decided that the Seahorse AUV would be used to deliver a payload to a team of special operations forces (SOF) on shore. In order to be able to accomplish this, it was determined that the Seahorse had to be operated on the surface to get sufficiently close to shore. The original design of the vehicle control software intentionally prevented running the propulsion motor on the surface and we had no experience with operating the vehicle on the surface in the presence of small waves. To support the payload delivery mission, the mission software was modified to add the capability for the AUV to arrive at a location at a specified time. This functionality along with the operation of the Seahorse in very shallow water was demonstrated during this test period.

In addition to testing of the modified Seahorse, NAVOCEANO completed installation and testing of a new launcher. The launcher was installed on the fantail of the USNS Mary Sears. The USNS Mary Sears is the newest of the T-AGS-60 class of survey ships operated by NAVOCEANO. The launcher is shown undergoing initial testing in Gulfport, MS, in Figure 7. The picture shows two Seahorse vehicles on the deck. During January 2002 both vehicles were operated from the USNS Mary Sears; although, as of this writing, NAVOCEANO has not operated two vehicles simultaneously.

Figure 7. Seahorse launcher undergoing trials

V. Giant Shadow Experiment

The Giant Shadow Experiment was geared to show the transformational role that a SSBN, modified to support SOFs in the field, could play in supporting future Navy missions. To support the experiment and to show the potential roles played by autonomous vehicles, the Seahorse conducted two missions. The first mission was to survey a route to be used by the SOF to infiltrate an island. The second mission was to transfer supplies and material both to and from SOFs on shore conducting a mission against a simulated weapons of mass destruction facility on shore. The entire operation was conducted on or near the Navy's AUTEC range near the Berry Islands during January 2003 from the submarine USS Florida with support from USNS Mary Sears.

The first mission commenced with the launch from the USS Florida on the AUTEC range. After the launch, the Seahorse surfaced to obtain a GPS fix and to permit support personnel to attach a range pinger as a safety device. After the range pinger was attached, the Seahorse resumed its mission. The route followed by the Seahorse is shown in Figure 8 where the starting point is in the west in about 300 meters of water. The

vehicle submerged and headed south to the first waypoint at constant depth and RPM for about 2.25 m/s. After reaching the first waypoint, the preprogrammed mission caused the vehicle to turn east and follow a course along the 50 m depth contour toward a point northwest of a simulated minefield. The Seahorse mission commanded the vehicle to transit through the minefield and then continue east to a point and surface. Although not designed for minehunting, the Marine Sonics sonar on the Seahorse did capture an image of a water-column mine. The first leg of this mission is colored in red in Figure 8. After remaining on the surface to transmit side-scan data to a host platform and waiting for permission to resume the mission, the AUV drifted to the east under the influence of wind-driven surface currents. The second part of the first day's operation was to survey the route to be followed by SOF forces to Great Stirrup Cay. This route is shown in green in Figure 8. During the first day, the Seahorse was operated for approximately 8 hours and covered about 36 km submerged. Recovery of the Seahorse aboard the USNS Mary Sears completed the day's operations.

The second mission performed by the Seahorse was to simulate a SOF re-supply and the return of a soil sample for shipboard analysis. The track of the Seahorse during this mission is shown in Figure 9. The Seahorse was launched at a position west of Great Stirrup Cay at night. The vehicle transited to a point about 500 m northwest of a cove on the island and loitered by circling. At a time calculated by the on-board software, the vehicle turned and headed toward the island where it surfaced just outside a cove, raised the mast that had been fitted with an infrared light, and drove about 75 meters into the cove on the surface. There the vehicle was met by a team of SOF and the payloads were removed from the Seahorse and replaced with a different set of bottles that had been filled with samples from shore. By the time this had been accomplished, the Seahorse had drifted significantly to the west and was in shallow water. The original plan called for the Seahorse to be restarted on its return mission by the SOF team in the cove. Because a detailed map of the area where the vehicle had drifted to had not been created, the Seahorse was towed to a point where there was sufficient water depth to submerge the vehicle. The Seahorse mission program was restarted at this point and the vehicle returned to its launch point for a 2:00 AM recovery aboard the USNS Mary Sears.

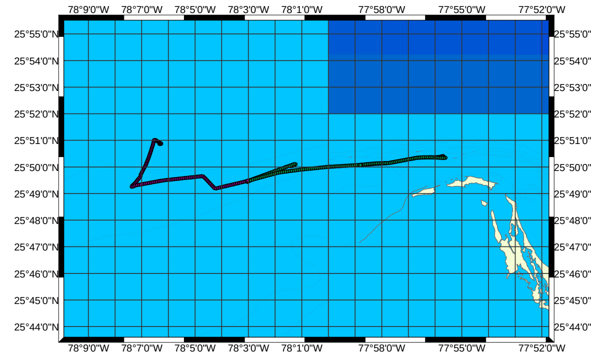

Figure 8. Map showing Seahorse route during survey mission

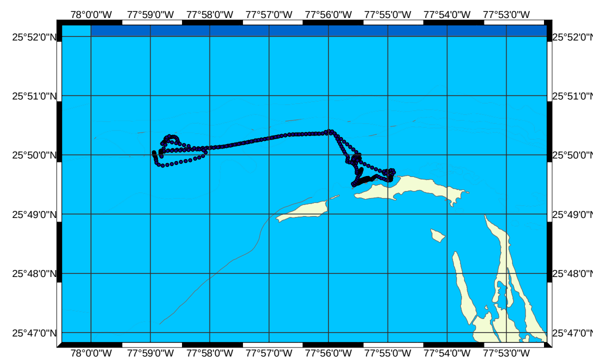

Figure 9. SOF resupply mission route

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